An Ice Strengthened Autonomous Surface Vessel for Surveying Marine-Terminating Calving Glaciers

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Approach with innovation

Colin Sauzé

Mark Neal

Tom Blanchard

Paul Miller

Sauzé, Neal, Blanchard and Miller describe an unmanned surface vehicle to be used for mapping and monitoring high risk marine environments.

Who should read this paper?

Anyone who is interested in the use of unmanned surface vehicles to access, map and/or monitor dangerous, delicate or inaccessible environments should read this paper. It should also be of interest to anyone interested in biologically inspired power management strategies.

Why is it important?

This work describes a small remotely operated unmanned surface vehicle (USV) equipped with high resolution swath bathymetry sonar and 3D laser scanners for producing 3D models (above and below water) of the fronts of marine terminated calving glaciers in Greenland. The vehicle has been coupled with an autonomous control system and biologically inspired power management strategies to increase its endurance. The vehicle is small, easy to handle, cheap and ice hardened. It is demonstrated to be a relatively stable survey platform that could be used in many different environments where it is not practical or is too dangerous for manned boats to operate. The authors offer insights into how to develop autonomous control systems and better power management strategies for USVs.

Although lagging behind AUVs (autonomous underwater vehicles) and UAVs (unmanned aerial vehicles), USVs are becoming increasingly available commercially, with perhaps as many as 200-300 in service today. There are no plans at present to sell the design presented in this paper, but enough information should be available in the paper for anyone with basic boat building and wood work skills to construct their own.

About the authors

Colin Sauzé is a Post-Doctoral Research Associate with the Department of Computer Science, Aberystwyth University. His current research interests include mobile robotics, ocean going robots, and biologically inspired systems. Mark Neal is a Senior Lecturer of computer science with Aberystwyth University, Aberystwyth, UK, where he leads the Intelligent Robotics Research Group. The majority of his research work has been in the use of bio-inspired algorithms for computation and control systems. Tom Blanchard received a BSc in artificial intelligence and robotics at Aberystwyth University, Wales, in 2011. He is currently a final year PhD candidate at Aberystwyth University, studying the field of biologically inspired control methodologies in wireless sensor networks. Paul Miller is an Associate Professor of Naval Architecture at the United States Naval Academy. He holds a BS in mechanical engineering from Tufts University, a master's degree in ocean engineering and naval architecture from Stevens Institute of Technology, and a doctorate in civil engineering from the University of California, Berkeley. His current research areas include small autonomous vessels, safety-at-sea issues and marine composite materials.

AN ICE STRENGTHENED AUTONOMOUS SURFACE VESSEL FOR SURVEYING MARINE-TERMINATING CALVING GLACIERS

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ABSTRACT

This paper describes a custom designed electrically powered, fully autonomous 2.73 metre long boat for survey and mapping tasks in locations unsuitable for larger, manned craft. This work was originally inspired by the desire to survey marine terminating calving glaciers in Greenland. The hull has been designed with a bump along the bottom to mount sonar transducers, to push away ice, and to achieve a top speed of around 4 knots. An autonomous control system has been implemented to allow for tele-operation, drive-by-wire, and fully autonomous modes with telemetry data relayed via a radio data link. To extend battery lifetime, a biologically inspired algorithm based on the mammalian endocrine system has been used. Several survey missions have been carried out successfully where the design has proved to be a suitable and low cost platform for survey and ocean mapping work.

KEYWORDS

Robot; Autonomous surface craft; Glacial survey; Biologically inspired power management; Artificial endocrine system

INTRODUCTION

This paper describes the development of a small autonomous boat designed for performing surveys in areas that are inaccessible by larger manned boats or that are too dangerous to use manned boats. The idea was originally inspired by the need to develop a boat capable of creating metre scale 3D models of both the above water and underwater portions of marine terminating calving glaciers. Marine terminating calving glaciers deposit ice directly into the sea and are one of the mechanisms by which the Greenland and Antarctic ice sheets are moving into the sea, potentially affecting future sea levels.

Building such models of these glaciers is key to understanding the rates of ice sheet depletion and the amount of ice entering the sea. Building high resolution 3D models requires being within hundreds of metres of the glacier front; this is a particularly dangerous environment for humans to operate due to the constant danger of falling ice and the large waves produced. This work follows on from previous work in 2010 [Neal et al., 2012], which produced a remote controlled boat for the same purpose; the shortcomings of this boat and the need for a custom designed autonomous replacement are discussed in the section entitled "Shortcomings of the Previous USV."

Small autonomous surface vehicles also have a number of potential benefits for other surveying missions where larger manned vessels cannot be used due to hazardous environments, shallow water, or difficulty accessing the target location. A number of other projects have already constructed unmanned surface vessels (USVs) for underwater surveying [Curcio et al., 2008], passive acoustic monitoring [Stelzer and Jafarmadar, 2012], and water quality monitoring [Dunbabin et al., 2009; Ferreira et al., 2012; Bars and Jaulin, 2012]. In addition to our previous work on combined sub-surface and above water systems, Leederkerken et al. [2010] and Ferreira et al. [2009] have demonstrated the feasibility of combining underwater sonar scans with above water laser scans to produce three dimensional models combining both above and under water features. The authors believe this to be the first example of such a vehicle being built specifically to operate in ice, perform glacier surveying, and simultaneous underwater and above water surveying.

Beyond the task of simply building a viable vehicle, many challenges still exist to the task of fully realizing truly autonomous surface vessels; these include collision avoidance [Bandyophadyay et al., 2009; Bruder et al., 2009; Stelzer et al., 2010], legal issues [Cruz and Alves et al., 2008; Showalter, 2004], and power management [Sauzé and Neal, 2008; Blair, 2010; Frey, 2009]. For operation in glacial areas, more advanced collision avoidance would be particularly useful and would dramatically reduce the dependence on human operators to avoid ice or to find paths through the ice. Although short term use close to a human operator is not significantly hampered by legal issues and power management, the transition to longer term autonomy and multi-day missions beyond the immediate supervision of an operator can be.

If multi-day unassisted autonomous transits to a survey site are required, then legal issues, power management, and avoidance of other traffic become much more important issues.

Shortcomings of the Previous USV

A previous attempt described in Neal et al. [2012] was made by the authors in 2010 to build a tele-operated unmanned surface vessel known as Minty and drive it along a glacier front while running a terrestrial laser scanner and swath bathymetry sonar system. Although able to generate valid survey data which fulfilled the requirements of the glaciologists and produce a 3D model of the glacier without any major gaps, this boat suffered from a number of shortcomings. As it was often tele-operated from the top of the mast on a yacht several hundred metres away, it was difficult to accurately maintain a straight course, determine the exact direction in which the USV was travelling, or to avoid small pieces of ice that the operator could not easily see. The USV was a modified Optimist dinghy with a covered deck and this did not perform well in the ice as it had a tendency to ride up onto the ice rather than pushing it aside. The hull also had a tendency to "crab" sideways instead of moving in the direction the hull was pointed. Propulsion was provided by a single Minn Kota Riptide electric trolling motor that was rotated by a linear actuator for steering; this did not provide enough propulsion to push against ice or to fight surface currents, such as those found in glacial melt water plumes. The linear actuator's response rate was also too slow for effective steering, especially for long distance remote control where the operator could not easily observe the boat. Power had been provided by two 110 amp hour and one 30 amp hour 12 V lead acid batteries; these provided enough power for four to five hours of surveying. To recharge the batteries, they had to be connected to a generator on the support yacht, which required lifting the USV out of the water and placing it on deck. The sonar transducers were placed on a frame suspended below the hull, which gave them a clear position for surveying but left them vulnerable to colliding with pieces of ice.

To overcome these problems, a new boat was created with a custom hull design that would address many of these shortcomings.

DESIGN AND CONSTRUCTION

Hull Requirements

Based on the experience with the previous USV, a number of design criteria for the new hull were developed. These were split into practical requirements for launch and recovery, payload/power/speed requirements, how the hull interacts with ice and water, and requirements for the build itself. Many practical requirements emerged from previous experience including the need for a durable watertight hull that can easily be hoisted onto the mother ship with a total weight of less than 200 kg and 140 kg of payload (including survey equipment, motors, batteries, computers, etc.). The height cannot exceed 1 metre, the beam 1.1 metres, and the length 2.75 metres to allow the boat to fit in a specific spot on the research vessel's deck. Lifting points and a strong towing point will be required to ease lifting of the boat onto the mother ship (and avoiding the time consuming use of slings) or towing it in the water. To perform the surveying mission,

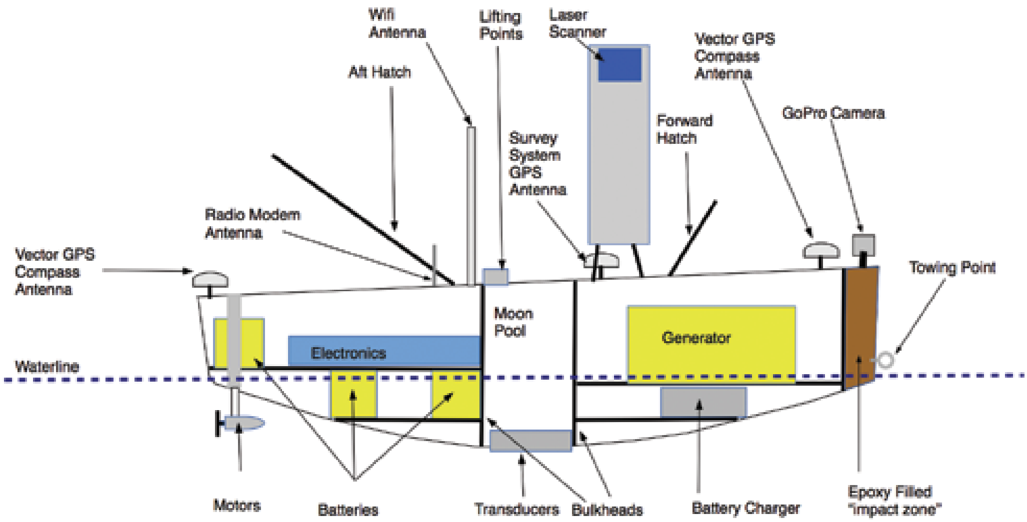

Figure 1: A schematic diagram of Minty2 and her internals. The side compartments are next to the moon pool and can be better seen as the circular white hatches in Figure 3.

sloped hull sections below the waterline amidships were required to mount swath bathymetry transducers at 30˚ from vertical and a horizontal mounting surface was required to mount the 17 kg Riegl Z620 laser scanner on deck. To allow for equipment (such as a CTD sensor) to be lowered into the water, a moon pool was placed in the middle of the boat with the hole being centred around a point between the transducers. The hull required good straight directional line stability and minimal roll and pitch to reduce the impact of motion on the captured data. High manoeuvrability and a target speed of approximately 4 knots were required to push away ice and to avoid obstacles before hitting them. The hull shape needed to be pointy enough to push through light brash ice and not accumulate it under the front of the hull.

Hull Design

To protect the hull from damage due to collisions from ice, submerged objects, or from being dragged onto a beach, the front third is covered in 2 mm thick aluminium cladding. The hull was reinforced with extra fibreglass below the waterline and the sharp (reinforced) bow combined with the outboard stepped deadrise was intended to minimize the impact zone and trapping of ice that would interfere with the sonar. The front 20 cm of the hull was filled with epoxy resin and thickener to create a solid impact zone that would take the brunt of any frontal collisions. A towing point was embedded inside the epoxy as it was the strongest point from which to tow the boat.

The hull was divided into four compartments: the aft compartment holds batteries and most of the electronics, two side compartments house the compass and survey inertial measurement unit (IMU), and a front compartment holds the generator. Figure 1 shows a schematic of the compartments and their contents. If either of the larger forward/ aft compartments floods, the hull should still remain afloat. The underwater portion of the hull also needs to shed bubbles to avoid interference with the sonar. Finally the entire system needs to be easily built on a low budget of approximately CDN$14,375 (including hull materials, fixtures and fittings, batteries, motors, computers, navigation sensors, and telemetry systems) and to be designed within three weeks and built in a month.

As with many design criteria sets, individual criteria were often in conflict and required trade-off studies. In this case the requirement for 4 knots was directly in conflict with the length restriction, the shape required for the below-water instrumentation, and the planned propulsion equipment. Propulsion was provided by two Minn Kota Riptide 45 (pound thrust) electric trolling motors using differential drive instead of rudders. The hull was developed from a basic, traditional skiff shape: a pointed bow, flat bottom with rocker, and a flat transom. This shape is easily built as a combination of developable surfaces, lending itself to plywood construction and yet is seaworthy and easily sheds ice. The requirement for both horizontal and 30˚ from vertical sloped hull sections below the waterline for the swath bathymetry transducers caused a major modification to the basic skiff shape.

Figure 2: Minty2 in construction, showing the plywood hull material, epoxy/E-glass sheathing being applied, and the unique hull shape with transducer bump.

Figure 2 shows the bump caused by the bathymetry mounting surface. The bump is faired into the hull to reduce drag but is integral to the hull rather than an external fairing. This allowed batteries to be stored lower in the hull, generating greater stability.

The need for high stability, volume for internal storage, and reserve buoyancy to offset ice buildup and extreme Greenland weather also forced an increase in beam. The small flat areas outboard of the bump served both as a means to increase stability and as a way to direct the generated bubbles away from the instruments. The flat sections also served as water guides to the two electrically driven propellers located on the outboard corners in a waterproof well just forward of the transom (the propellers have not yet been mounted in Figure 2). With the low centre of gravity and the wide beam,

Figure 3: The completed boat on her maiden voyage.

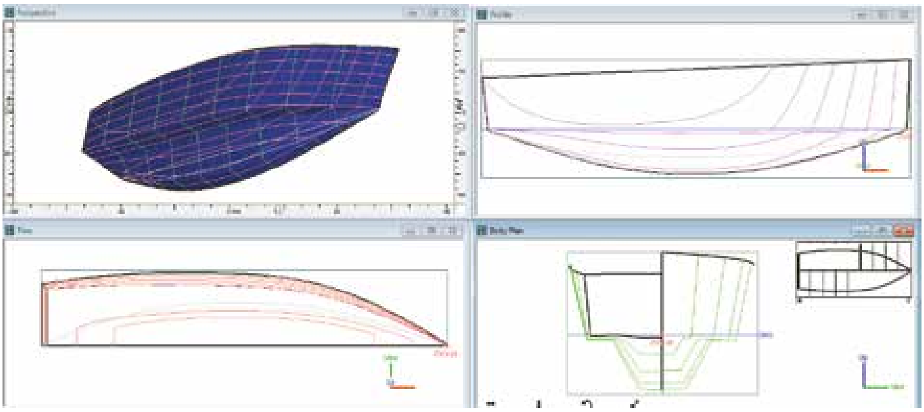

Figure 4: Perspective (top left), waterline (bottom left), profile (top right), and body (bottom right) plans of Minty2. The transducer housing bump is particularly noticeable in the body plan.

Minty2 was calculated to heel to 123˚ without capsizing (about the same as an offshore sailing yacht). A formal incline experiment was not performed but heel angles were checked against some simple cases in stability models. The design iterations focused on trying to reduce drag while maintaining stability and keeping the instruments free from ice and bubbles. The final lines are shown in Figure 4 and the principal characteristics are shown in Table 1. Vertical centre of gravity (VCG) (shown in Table 1) was estimated using a weighted moments tabular method comprising all components that weighed over two kilograms.

Power and Propulsion

Propulsion is provided by a pair of Minn Kota Riptide RT 45, 12 volt electric trolling motors mounted on either side of the boat at the stern. These steer through differential propulsion and are controlled by a pair of 4QD VTX 40-12 motor controllers. Power is provided by three 12 volt, 90 amp hour LiFEPO4 batteries, which power the control system electronics and propulsion. These can be recharged using a Kipor IG1000 1 KW petrol generator connected to a 240 V mains AC charger; both of these are mounted in the forward compartment. Optionally an additional 12 volt, 40 amp hour lead acid battery can be placed in this compartment to power the survey system independently. This ensures

Characteristic	Value	Units
Length Overall	2743	mm
Maximum Beam	990	mm
Displacement	200	Kg force
Draft Amidships	294.5	mm
Waterline Length	2691	mm
Beam max extents on WL	829.5	mm
Wetted Area	2.47	m^2
Max sect. Area	0.13	m^2
Waterpl. Area	1.82	m^2
Prismatic Coefficient (Cp)	0.59	
Block Coefficient (Cb)	0.31	
Max Sect. Area Coefficient (Cm)	0.53	
Waterpl. Area Coefficient (Cwp)	0.81	
LCB %	-53.6	from stem
LCF %	-58.2	from stem
VCG	54	mm above DWL
RM at 1 Degree	1.17	kg.m
Length to Beam Ratio	3.2	
Beam to Draft Ratio	2.8	
Length to Ratio	4.6	
Propulsion	400	Newtons

Table 1: Principal characteristics of Minty2.

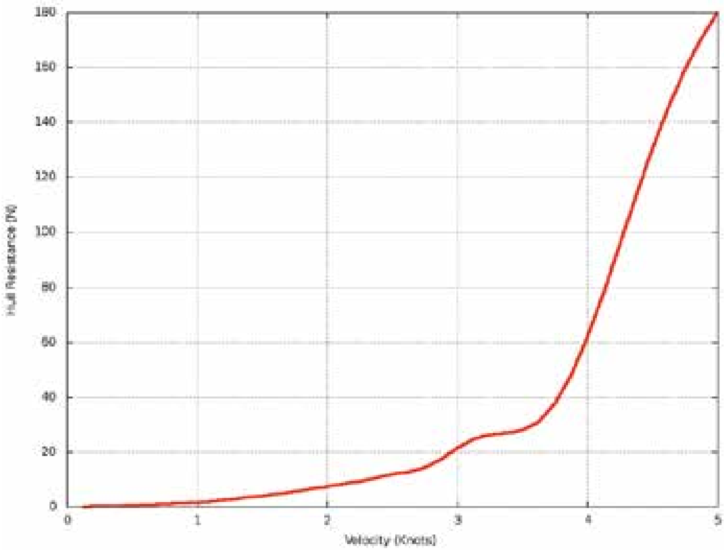

Figure 5: Minty2's predicted resistance using van Oortmerssen's method.

that the survey system cannot discharge the propulsion batteries and that the readings generated by the survey equipment are not adversely affected by electrical noise or voltage fluctuations from changes in motor speed.

The theoretical 400 Newton thrust rating from the electric trolling motors is based on the power consumption rather than the output from the propellers. The trolling motor itself claimed an electrical motor efficiency of 80%. Of the available propellers for these motors, the three-bladed propeller designed for maximum efficiency was near 65%, while the two-bladed propeller designed to shed weeds (and ice) was close to 40% efficient [Comstock, 1967 – pages 411-422]. These are open-water values, however. Another efficiency loss is due to the propeller location behind the motor pod and vertical shaft, which disturbs the flow into the propeller. A typical value for this loss is 25%. The final major loss in thrust is due to the disturbed water in the hull wake. This thrust deduction is typically around 20% for a streamlined hull but can be as high as 29% [Comstock, 1967 – page 391]. Thrust was estimated at 68 N: 400 N x 0.8 (electrical efficiency) x 0.4 (propeller efficiency) x 0.75 (motor pod and shaft disturbance) x 0.71 (hull wake disturbance) = 68 N. The total propulsion efficiency is therefore approximately only 17% of the rated thrust value for a typical ship hull.

Figure 5 shows the predicted resistance curve for Minty2. Time and budget did not allow for tank testing a model, which would be the normal method for predicting the resistance of an unusual hull shape like Minty2's. Although none of the common parametric prediction methods claimed to include hulls like this one, the most applicable one – based on slow speed, heavy fishing boats, and tugs – was van Oortmerssen's [1971] method, which was used with the understanding of high uncertainty. With the 68 N available, her predicted top speed using that method was approximately 3.9 knots, just under the design criterion. As will be discussed later, even this speed was a bit optimistic due to challenges in fairing the transducers.

Evaluating Hull Performance

Informal observations from operation in Greenland showed that the hull was far better at pushing aside ice than the Optimist dinghy hull used in the original Minty. It is difficult to quantify this numerically, especially when both hulls were not available simultaneously for a side-by-side comparison, as logistical and

Figure 6: The hull before and after the skeg was attached.

financial constraints meant it was not possible to bring both boats to Greenland (or anywhere else) simultaneously. To test the performance predictions of the hull design, a series of tests were carried out on inland lakes in Wales. The maximum speed recorded from the GPS during these was around 3.4 knots and this was achieved under full power, on a calm day while testing the boat with the larger 117 KHz sonar transducer installed. This is lower than the predicted speed of 3.9 knots. Numerous possibilities exist for this lower speed but were not explored, including actual propeller thrust and efficiencies, a lack of fairing on the transducers, and, most likely, an under prediction of resistance from van Oortmerssen's method due to the large transducer fairing bump.

The maximum speed of the boat was adversely affected by switching to a smaller 468 KHz sonar transducer, which left a gap in the transducer mounting area and reduced the top speed to around 3 knots.

Early experiments showed that the hull could be difficult to turn accurately and keep on a straight course, especially for the autonomous control system. Although this may have been solvable through improvements to the autonomous control system and heading sensor, a skeg of 570 cm^2 was added to the underside of the stern between the motors. Its length represents around 11% of the transverse projected under the water area of the hull. Photos of the hull with and without the skeg can be seen in Figure 6. Installing this skeg produced dramatic improvements in the ability to stay on a straight course, while still allowing the boat to turn.

An experiment was performed to test the power consumption over the propulsion system in order to estimate the maximum range and endurance. Table 2 shows the power consumption in joules per metre travelled against three different target speeds: 1.5 knots, 2 knots, and 2.5 knots. These measurements were taken with the 468 KHz transducer installed and so do not reflect the absolute maximum speeds possible if either the larger transducer was installed or

Target Speed	Power Consumption per Metre
1.5 Knots	126.035 J/M
2.0 Knots	165.478 J/M
2.5 Knots	205.634 J/M

Table 2: A comparison of the number of joules per metre used by the motors running the same course with different target speeds.

Component	Current	Voltage	Energy per hour
Control and Communications System	2.2 A	12 V	95 KJ / H
Survey System	4 A	12 V	172.8 KJ / H
Total	6.2 A	12 V	267 KJ / H

Table 3: Details of the power budget for the control system and survey system.

Target Speed	Distance	Time
2.5 kts (4.63 km/h) – with survey system	44.27 km	9.56 hours
2.0 kts (3.70 km/h) – with survey system	49.05 km	13.24 hours
1.5 kts (2.78 km/h) – with survey system	52.43 km	18.87 hours
2.5 kts (4.63 km/h) – without survey system	51.57 km	11.14 hours
2.0 kts (3.70 km/h) – without survey system	61.02 km	16.48 hours
1.5 kts (2.78 km/h) – without survey system	72.79 km	26.20 hours

Table 4: The estimated maximum range and endurance time of the system based on extrapolations of the data from Tables 2 and 3. Figures without the survey system are included as this is usually powered from its own separate battery, but can be powered from the main battery, if required.

something else was used to block the recessed area and make it flush with the rest of the hull. A north/south oriented grid course of approximately one kilometre total in length was repeated at each of the target speeds under autonomous control: the boat was moved back into the same start position for each run. Power consumption was recorded using the current transducers and voltage sensor and the total energy used from the batteries was calculated for each of the courses. Table 2 presents the normalized results of this experiment showing the number of joules consumed for each metre travelled.

Given this data we can calculate the theoretical range and endurance time of the boat, given that it is equipped with three 12 V, 90 Ah (11.6 MJ) batteries. We must also include the power consumption of the control and communications system and the survey system, which are summarized in Table 3. Table 4 presents the maximum range and endurance time for each of the three target speeds both with and without the survey system being powered from the main batteries. It should be noted that in reality the maximum range will not quite meet these estimates as the voltage drop which occurs as the batteries reach the end of their discharge cycle will most likely cause computer equipment to power down and will slow down the motors. We expect that in reality we should be able to achieve 80% to 90% of these estimated ranges under ideal conditions. Winds, waves, and currents can also reduce the total range. The figures presented in Table 2 were obtained in a small lake with little current – only small waves and a head/tail wind gusting between 8 and 20 knots. Even if we assume these factors reduce range by 50%, this still leaves a range of between 22 and 36 kilometres and several hours, which should be more than sufficient for most glacier, lake, and coastal surveying missions.

Hull performance in high winds also suffered due to the high freeboard, which effectively turned the hull into a sail, making staying on course very difficult. This was the result of early design decisions to leave plenty of space for equipment. However, it turned out that the equipment used was small enough that the freeboard could have been nearly halved without causing any problems, although this

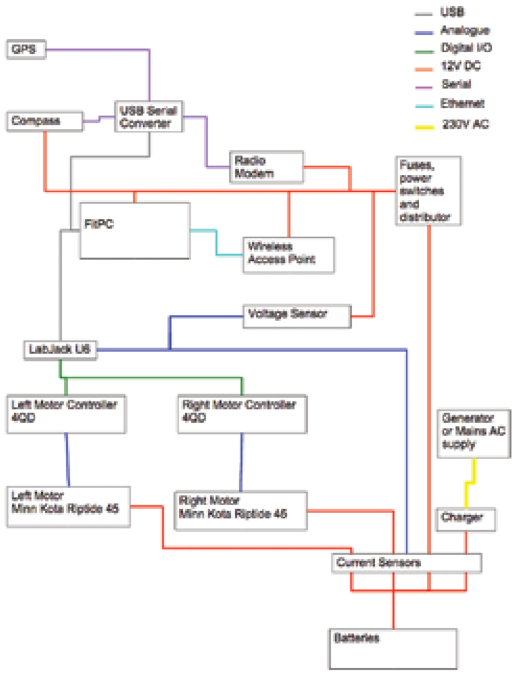

Figure 7: A diagram showing more detail of the connections within the control system and its power monitoring sub-system.

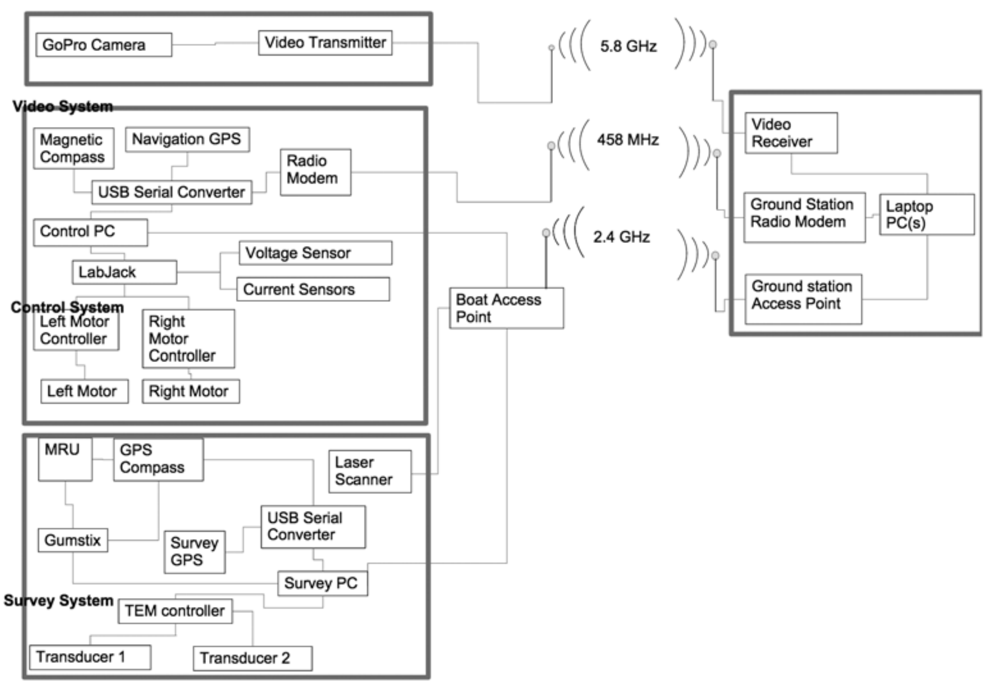

Figure 8: A diagram showing the data connections between all the systems within the boat.

could have led to waves breaking over the hull in open water. A more conservative reduction would be to aim for a traditional rule of thumb for a ratio of 1:7 between the freeboard and the boat length; this would have reduced the freeboard by approximately 13%.

CONTROL SYSTEM

Control System Hardware

The autonomous control system runs on a FitPC2 embedded PC using a 1.6 GHz Intel Atom processor, two gigabytes of RAM, and running Ubuntu Linux 12.04 LTS. A LabJack U6 USB I/O board sends control signals to the motor controllers and reads analogue voltages from a multi-channel current sensor and a voltage sensor. A four port USB serial converter connects a Furuno PG-500 Fluxgate compass, Garmin GPS 18, and a X8200 458 MHz radio modem to the PC. The PG-500 compass eventually developed a fault and was replaced with a Honeywell HMC6343 solid state compass connected to an Arduino Uno microcontroller which emulated the PG-500's National Marine Electronics Association (NMEA) strings. For operating in Greenland where the magnetic field is too weak to use for navigation, heading information can be provided from a Hemisphere Crescent Vector GPS compass that also produces an NMEA data stream similar to the PG-500's or if necessary from the course-made output from a 5 Hz GPS receiver (which is only reliable once the boat is moving). The PC is also connected via ethernet to an 802.11b/g/n (wifi) wireless network access point, which allows remote access to the PC and also connects to a separate survey system PC. Two 9 dB high gain omnidirectional antennas on the boat (and optionally another pair at the ground station) allow this signal to be picked up over a range of several kilometres, providing there is a good line of sight. Figure 7 shows how the entire system connects together with more detail of the control and power monitoring system shown in Figure 8.

A secondary goal for the boat was to develop power management algorithms, so the ability to accurately monitor the power consumption of individual components was important. A pair of Pedal Powered Generators H5A-ACDC inductive five channel current sensors and an Attopilot 13V45A voltage and current sensor are used for this purpose. The H5A-ACDC is configured to individually measure the current used by each motor, the control system board, and the charging circuit. This leaves another six channels free, which could potentially be used in future to measure the current used by individual pieces of survey equipment. The Attopilot sensor is used to measure the battery voltage; its current measurement features are not used.

Control System Software

The main control system software was based upon a system already used in autonomous sailing robots built by Aberystwyth University [Sauzé and Neal, 2011A; 2011B]. It runs on the FitPC and works across five parallel threads. One of these is responsible for reading the latest position and speed from the GPS, another for reading the heading from the compass and corrects it for magnetic deviation based upon the GPS location using the US National Oceanic and Atmospheric Administration World Magnetism Model library [Chulliat et al., 2014], a third for reading the current and

```
targetHdg=headingToWaypoint();  //Get  the  target  heading  to  the  current
waypoint

hdgErr=getHeadingDiff(heading,targetHdg);  //Calculate  how  many  degrees  off
course we are.

hdgErr=hdgErr+constrain(xte*xteGain,-xteLimit,xteLimit);  //Add  on  the  cross
track error, constraining it to between the limits

spdErr=targetSpeed-speed; //Calculate speed error

setpoint=constrain(setpoint+(-spdErr*speedGain),127,225);   //Calculate   the
motor set point

runningErr=constrain(runningErr+hdgErr,-iLimit,iLimit); //Calculate error for
integral controller

lSpd=constrain((hdgErr*pgain)+(runningErr*igain),-127,127);  //Calculate  left
motor speed

lSpd=constrain(setpoint+lSpd,0,255);

rSpd=constrain((hdgErr*pgain)-(runningErr*igain),-127,127);  //Calculate  right
motor speed

rSpd=constrain(setpoint-rSpd,0,255);
```

Algorithm 1: The proportional-integral controller used to control the boat heading and speed.

voltage from the LabJack, another for reading telemetry commands arriving over the radio modem and a UDP socket on the ethernet/wifi, and finally the main thread performs the control system logic determining motor speeds and sending target motor speed commands to the motor controller via the LabJack's Digital to Analogue converter. The control system has three modes of operation: a fully manual mode where the motor speeds are directly remotely controlled via telemetry commands, a drive-by-wire mode where a target heading and speed are sent via telemetry commands, or a fully autonomous mode where a mission plan consisting of a series of waypoints is followed. In autonomous mode, each waypoint consists of a target latitude and longitude to reach, a threshold distance that the boat must get within to consider it has reached the waypoint, a target speed at which to move, and the amount of time that should be spent waiting at the waypoint once it is reached. If this time is non-zero then the boat will attempt to stay as close as possible to the waypoint position; if it drifts away from it, then it will start to increase its target speed in order to get back to the waypoint.

In autonomous and drive-by-wire modes, a pair of proportional-integral (PI) controllers adjust the speeds of both motors to reach both the target heading and target speed. A description of this algorithm is included in Algorithm 1. In autonomous mode, the target heading is calculated as the great circle route from the current GPS position to the next waypoint; in drive-by-wire mode, it is simply the heading specified by the user. The target speed is specified in knots and measured as speed over the ground from the GPS receiver. This only gives accurate readings above a speed of approximately one knot, so target speeds of less than one knot cannot be reliably achieved. Pseudo code for the control algorithm is shown in Algorithm 1. The gain values of the controllers were tuned through a manual iterative process instead of using a mathematical tuning method such as Ziegler–Nichols, as it was relatively simple to tune the controllers in the boat during initial testing. The parameters used were a proportional gain of 0.3, an integral gain of 0.005, and a (proportional) speed gain of 1.5.

Telemetry and Remote Control

Telemetry data is sent both via the ethernet (and subsequently onto the wifi network) and the radio modem at a rate of 1 Hz; this can be displayed by ground station software on a laptop computer. Each piece of data is sent as ASCII text in a key/value pair with the format key=value. To reduce bandwidth requirements (the radio modem only operates at 1,200 bits per second), only those values which have changed are usually sent. To ensure all data gets through, a full message is sent once every 10 seconds. The ground station is highly configurable and allows the user to specify which data elements they wish to view and can select to have these shown as a gauge, graph, or text value. A moving map display is also shown with the boat's current position along with its current set of waypoints. A number of parameters are transmitted including GPS position, compass heading, motor speeds, GPS speed over the ground, current and voltage sensor readings, and waypoint information. The ground station software can issue commands to the boat that can switch between the manual, drive-by-wire, and fully autonomous mode as well as sending commands to alter motor speeds and upload new waypoints. The user can also steer the boat through the laptop's arrow keys, although latency issues make doing this in manual mode difficult. To allow for sudden emergency movements to be made, a special telemetry command exists to nudge the boat left or right temporarily; when this is received by the control system, it will turn the appropriate motor to full power while leaving the other motor off for five seconds. This command does not change the mode of operation; so if activated in autonomous mode, the boat will then return to its original course.

Vision System

As it is envisaged that the operator may be several hundred metres or even a few kilometres from the robot and that they need to detect obstacles such as ice, a wide angle (180˚) GoPro Hero2 HD camera has been installed on the front of the boat. The analogue output of this is directly connected to a 5.8 GHz video transmitter, which is received at the ground station and displayed on a laptop using a Hauppauge WinTV USB-Live2 video input adapter. This video stream is also recorded both at the ground station and on the boat for reviewing missions. It would have also been possible to connect the camera directly to the control system FitPC using a USB video input adapter and stream the video back over the wifi link. However, this would have introduced latency and potentially saturated the data link, which was primarily intended for remotely connecting to the survey PC.

Improving Control System Accuracy

The first implementation of the control system simply followed a target heading computed by the great circle bearing from the current position to the next waypoint. This was calculated using the formula shown in Equation 1 where $\varphi 1$ is the longitude and

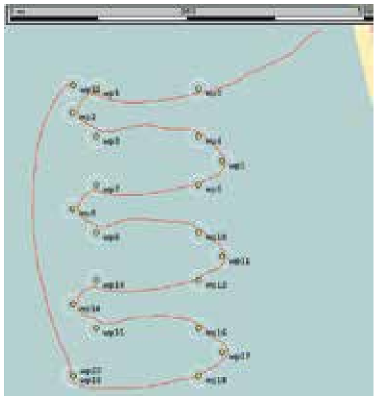

Figure 9: A map showing a survey pattern being followed using only a heading controller. The white circles around each waypoint indicate the threshold distance and the red line indicates the path taken.

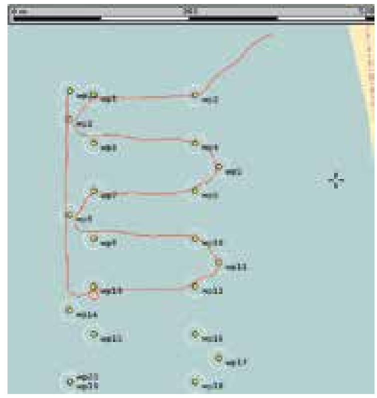

Figure 10: A map showing a survey pattern being followed using the cross track error minimization controller. The white circles around each waypoint indicate the threshold distance and the red line indicates the path taken.

λ1 is the latitude of the current position, φ2 and λ2 represent the waypoint's position, and *h* is the heading from the current location to the waypoint. This formula was obtained from Williams [2011]. Although this would lead the boat on a course that would eventually reach the waypoint, relatively large cross track errors (the distance from the line between the last waypoint and current waypoint) would only generate a small error between the target heading and actual heading when the boat was some distance from its waypoint.

$$h = \mathrm{atan2}(\sin(\varphi 2 - \varphi 1)\cos\lambda 2, \cos\lambda 1 \sin\lambda 2 - \sin\lambda 1 \cos\lambda 2 \cos(\varphi 2 - \varphi 1)) \qquad (1)$$

Inspired by work from Jaulin and Le Bars [2012], we adopted an approach to follow a line between two points instead of a target heading. This was achieved by calculating the cross track error, multiplying it by a gain value, and adding this to the target heading; this way the target heading would be adjusted to always keep the boat close to the line between the current waypoint and the previous waypoint. Cross track error was calculated in kilometres using the formula shown in Equation 2 and was obtained from Williams [2011]. In this formula *A* is the previous waypoint, *B* is the next waypoint, *C* is the current location, and *t* is the cross track error. This gives a value which is positive if the boat is to the left of the target line (visualizing the line as run up/down) and negative if it is to the right.

$$t = \mathrm{asin}(\sin(\mathrm{distAC})\sin(\mathrm{courseAD} - \mathrm{courseAB})) \qquad (2)$$

The new target heading is computed with the formula *h*=*e*+(*t***gain*) where *e* is the error between the current heading and waypoint heading as computed by the PI controller, *t* is the cross track error in kilometres, and *gain* is the cross track gain. Manual tuning showed a value of 1,750 to be a reasonable gain, which equates to turning 1.75˚ towards the target line for every metre of cross track error. The maximum cross track error was also capped at 90/*gain* metres to prevent a correction of more than 90˚ from being applied.

To test the effect of this upon the control system accuracy, a test course was setup with a survey grid style pattern running west for approximately 200 metres, then turning south for 100 metres, west for 200 metres, and south for an additional 100 metres. Three repeats of this pattern were carried out before turning

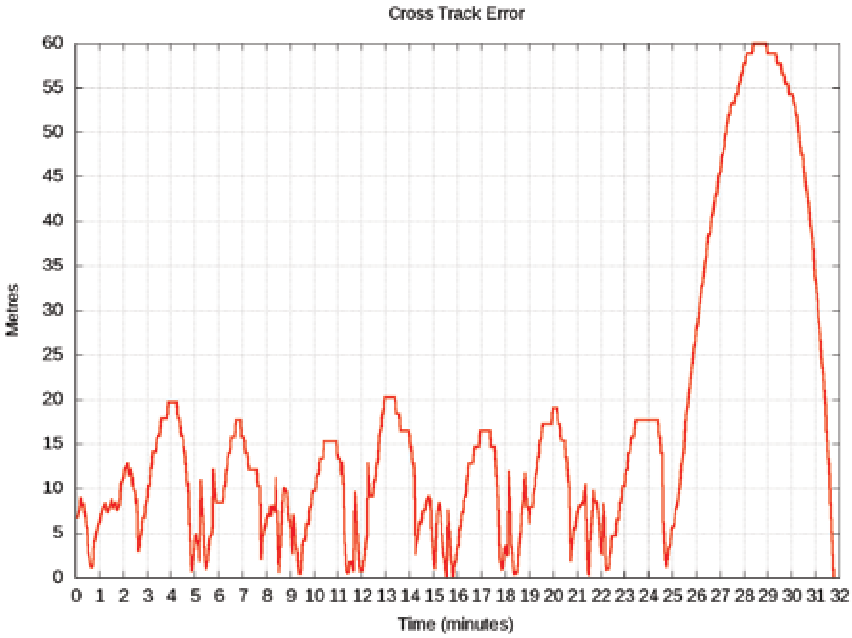

Figure 11: A graph showing the cross track error in metres against time using only the heading controller. This is the same course shown in the map in Figure 9.

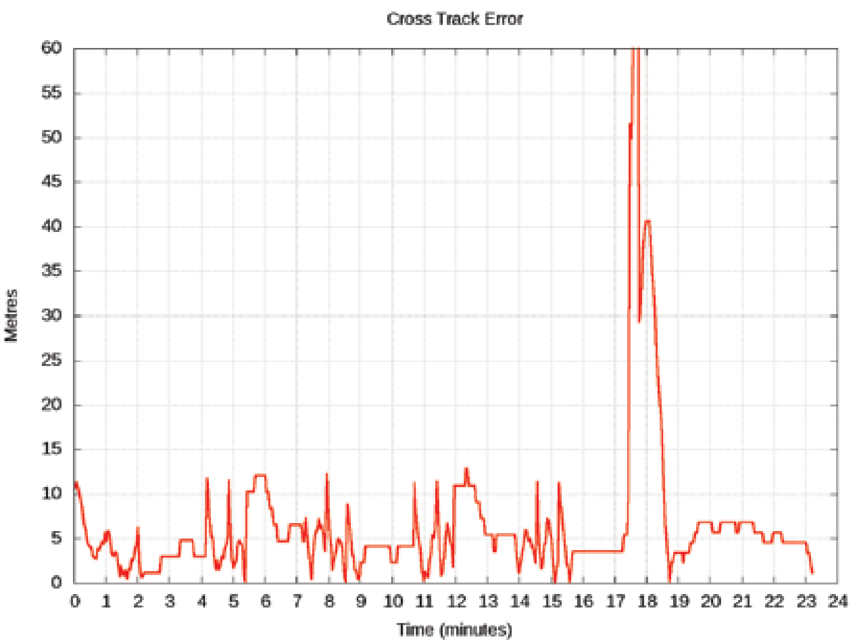

Figure 12: A graph showing the cross track error in metres against time using only the heading controller. This is the same course shown in the map in Figure 10.

north for approximately 500 metres to rejoin the western end of the first east to west line; this course can be seen in Figures 9 and 10.

The experiment was conducted in the sea to the west of Aberystwyth, Wales, on July 23, 2013, with a smooth sea state and a gentle Beaufort Force 2 wind from the south. This course was then run with both controllers and their cross track error values compared; Figures 9 and 10 show a map of the course taken and Figures 11 and 12 show the cross track error value. The last east/west portion of the grid had to be cancelled on the experiment run with the cross track error minimization turned due to time constraints for re-entering the harbour before low tide. The small loop around waypoint 13 in Figure 10 and the spike in cross track error at 17 minutes in Figure 12 are due to a sequence of skip waypoint commands being sent.

As can be seen in Figures 10 and 12, the cross track minimization kept the error level within 12.5 metres, while it had been up to 60 metres without minimization. This is particularly visible in the maps where the large arc to the west in the northbound part of control run (Figure 9 from waypoint 20 to 21 turns into a straight line in Figure 10). The mean cross track error was 16.65 metres for the control run and 6.71 metres for the experiment run; discounting the portion of the log data around 17 minutes where the skip waypoint commands were being issued reduces it to 4.63 metres.

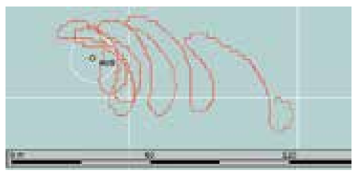

Figure 13: A map showing the effects of a strong cross wind on the cross track minimization algorithm, where the boat spends most of its time trying to return to its target course instead of progressing towards the waypoint.

These improvements demonstrated an ability to sail precise courses approaching the accuracy of the consumer grade GPS receiver in the navigation system in calm weather. However, other tests in stronger winds and rougher seas showed that the cross track minimization could actually be a hindrance as considerable time and effort was spent counteracting minor shifts in the cross track distance at the expense of making any progress towards the waypoint. It could be argued that such conditions are outside of the intended operational parameters for such a boat and that what was really required at this point was a boat with less windage and more powerful propulsion. An example of this is illustrated in Figure 13, which shows a GPS track of a short course attempted during the 2013 World Robotic Sailing Championships in Brest, France, on September 6, 2013. This course was undertaken during a gusty day with wind speeds of Beaufort Force 3-4 from the southwest and waves of approximately 20-30 cm. The boat is struggling to maintain a straight line, is constantly being blown off its target line, and spends most of its time trying to correct back onto this course rather than making any progress towards the waypoint.

SURVEY SYSTEM

Survey System Design

As in the previous work detailed in [Neal et al., 2012], the survey system is made up of two components: an SEA SWATHplus-L 117 KHz multibeam sonar for underwater surveys and a Riegl z620 terrestrial laser scanner for above water. The sonar has a maximum range of approximately 500 metres and the laser scanner has a range of two kilometres. Between the two systems, an almost complete three dimensional model of the surrounding area both above and below water can be made. Some later experiments were run with a 468 KHz sonar transducer, which offered better resolution at short distances but is a physically smaller transducer and does not entirely fill the gap that was designed to fit the larger 117 KHz transducers. This left a

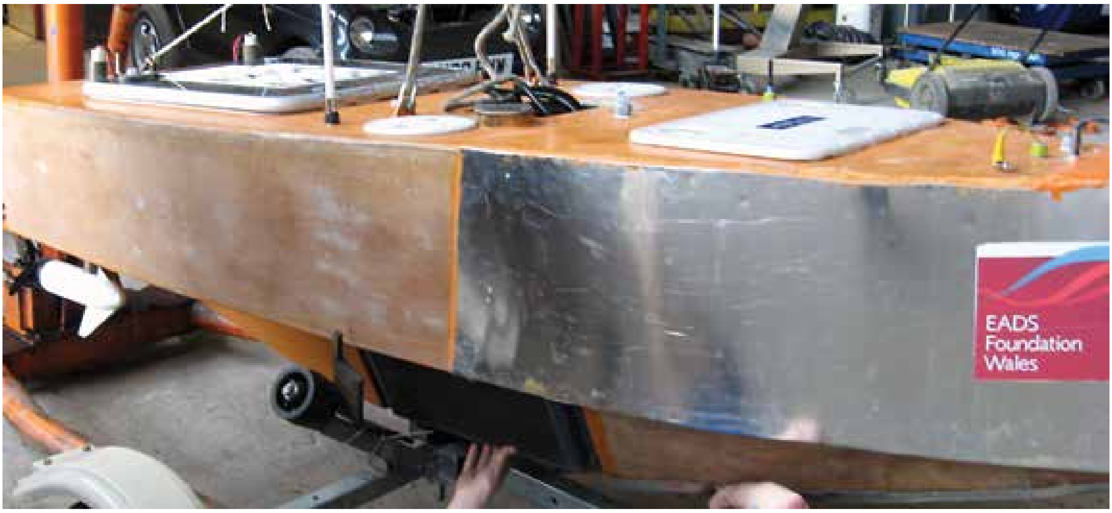

Figure 14: A photo showing the hull with the larger 117 KHz sonar transducer installed. The transducer is the grey box about half way along the bottom of the boat.

Figure 15: A photo of the smaller 468 KHz sonar transducer installed in the gap left by the 117 KHz transducer.

recessed area in the side of the hull, slowing the boat down. Figures 14 and 15 show the difference in size between the two transducers and the gap left around the 468 KHz model. Data from both systems is processed using a second FitPC2 with a 1.6 GHz Intel Atom processor and running Microsoft Windows 7. Although this places a heavy load on the CPU, it is still able to perform a survey without dropping any data. The FitPC also provides a very small form factor and low power consumption.

Surveys in Greenland

In July 2012, Minty2 was taken to Greenland to attempt a survey of the Lille Glacier near Uummannaq on the west coast of Greenland. Unfortunately, a combination of technical problems with the radio modem and GPS compass and unfavourable weather conditions prevented any survey of the glacier from taking place. A short test survey was performed and this demonstrated that Minty2 was able to break through loose brash ice with relative ease. The problem of ice accumulating under the hull as had been observed with the original Minty did not seem to be a problem. Several collisions with small icebergs occurred and, apart from a superficial scratch to the aluminium cladding, no damage was caused. The lifting points and generator charging saved significant time in recovering her onto the mother ship and recharging the batteries. Despite not being able to run any useful surveys, this experience did show the hull design to be better at coping with the conditions faced in Greenland.

Surveying Missions Beyond Greenland

Minty2 has since been used for several other survey missions in the UK. These have all focused on underwater surveying with the 468 KHz swath bathymetry system. The first of these missions took place in Aberbach, Pembrokeshire, in southwest Wales and was aimed to locate the wreck of the *Charles Holmes*, a wooden ship wrecked during a storm in 1859. The approximate location of the ship's remains was known, but the exact location was not known. Because of the relatively shallow water and proximity to rocks, it was not possible to bring in a larger manned vessel to perform the survey. Figure 16 shows

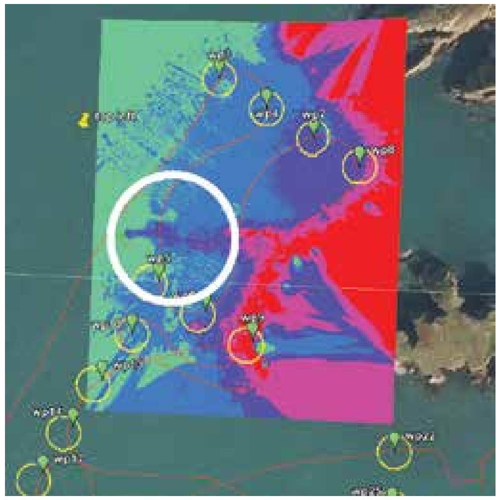

Figure 16: Interpolated bathymetry data overlaid onto an aerial photo of the Aberbach area and the wreck of the *Charles Holmes*. The area circled in white is believed to be the wreck site.

a bathymetric depth map of the area and highlights the area believed to be the wreck, although being over 150 years old the wreck has few distinguishing features and it is difficult to confirm this find without sending in a team of divers. A second mission took place in the Scottish Highlands with the aim of surveying several small, remote lochs looking for submerged ancient trees for a dendrochronology project. In both of these cases, a smaller boat would have probably been suitable and the size and weight of Minty2 proved to be a hindrance. In the Aberbach mission, Minty2 had to be driven approximately 7 kilometres by sea to the survey site as it was not possible to launch her nearby due to access restrictions, including a 100 metre walk down a steep and narrow path between the nearest road and the water. In the Highlands, large vehicles had to be taken down narrow unpaved roads. Minty2 then had to be wheeled the last few hundred metres on her trailer across boggy and uneven ground before being launched and recovered along an almost shear drop into the water. If a smaller and lighter boat had been available, then it could have simply been carried down to the water. Applications such as these, where the aim is simply to locate an object for further investigation rather than to build centimetre accurate models, would be more suited to smaller, lighter, and cheaper side scan sonar systems instead of a swath bathymetry system. This, coupled with not needing the laser scanner, would allow for a smaller and lighter boat that could be deployed without a trailer and carried in the back of a large car.

POWER MANAGEMENT

The results in the "Power and Propulsion" section suggest that reducing speed can significantly extend the boat's range. In imagining scenarios where greater autonomy would be required, it would be useful if an intelligent power management system could reduce power consumption to extend range when required. It would also be potentially useful if such a system could automatically suspend surveying and switch on the generator and recharge the batteries. It would not be possible to survey with the generator on due to the noise it causes both electrically and acoustically that interferes with the sonar. Previous work [Sauzé and Neal, 2013] has shown that an approach inspired by the mammalian endocrine system can be used to manage power in robotic systems and reduce power consuming activities in response to falling battery levels and mission demands. This approach is modelled upon the regulation of blood glucose levels by the hormones insulin and glucagon, which act in tandem to modulate activities depending on the available energy levels. When blood glucose is low, glucagon is released to stimulate the liver into breaking down glycogen (stored fat) cells into glucose and to suppress energy consuming activities. When glucose levels are high, insulin is released to signal to cells to try and use up the excess glucose and for the liver to convert it into glycogen.

In an artificial endocrine controller, artificial hormones are signals which produce changes in the behaviour of target systems by either suppressing or promoting (modulating) the activity they represent. This model offers a (near) continuous, analogue style response to power management as opposed to many traditional approaches which use a few defined power saving modes and a normal mode of operation, although it can also create dramatic behavioural changes when more Boolean behaviours are required. In previous robotics work with solar powered sailing robots [Sauzé and Neal, 2013], power consuming activities were gradually suppressed or promoted depending on battery and sunlight levels. This allowed the robot's behaviour to gradually adapt to changing energy levels and predicted energy levels that were based upon predictions of the available sunlight.

The power consumption of Minty2 was analyzed using the proprietary Tethys power management design methodology [EADS, 2014], which is designed to aid the design of artificial endocrine controllers by determining which systems to modulate, the extent to modulate them, and providing the values of the artificial hormones which drive that modulation. This analysis identified that the propulsion system was both the main consumer of power (at 87% of the entire power budget) and the best candidate for modulation to save power. Power consumption could be controlled by modulating the target speed in proportion to the battery level and when the battery level fell dangerously low that the generator would be automatically switched on, surveying suspended, and the boat would enter a low power station keeping mode until the battery had been recharged significantly.

Speed Modulating Controller

A linear function was generated to determine the release rate of the hormone; it governs how much hormone is created in response to a given input. In this case, the input will be the battery state of charge. In Equation 3, h is the amount of hormone to be released and b is the battery state of charge as a percentage value between 0 and 100. As the intention is to suppress the system as the battery depletes, this function gives an output between 0 and -1. The maximum level of modulation (-1) is reached when the battery reaches a 20% state of charge, in accordance with the manufacturer's guidelines to not discharge below this level and it will give zero modulation above 90% state of charge.

$$h=0.0143b-1.2857 \tag{3}$$

This released hormone value was then applied to the function in Equation 4 to calculate the level of free running hormone in the "bloodstream." This function has the effect of both decaying the amount of hormone in the bloodstream and limiting the amount that a new release of hormone can have on the overall quantity in the bloodstream. A more in-depth discussion of this function can be found in chapter 5 of Sauzé [2010]. In this function, h is the quantity of hormone as determined by Equation 3, c_t is the current concentration of free running hormone, c_{t+1} the future concentration of it, and r is the decay/release rate, which controls how quickly the levels of free running hormone will change. For the purpose of this experiment r was set to 0.0005.

$$c_{t+1} = c_t - r(c_t - h) \tag{4}$$

The hormone in the bloodstream was then used to modulate the target speed of the boat. Equation 5 calculates the new target speed of the boat s, by taking the initial target speed t (as had been specified by the user) and adding it to the sensitivity (0.65375 in this case) multiplied by 2.8 times the bloodstream hormone concentration c that was calculated in Equation 4. For a waypoint with a target speed of 4 knots, this would result in the target speed being reduced to 2.17 knots when the battery is at or below 20% state of charge. The value of 0.65375 was calculated by the Tethys system [EADS, 2014] and the importance it had assigned to the activity of driving to a waypoint. Had a sensitivity value of 1.0 been used, then the target speed would have been zero when the battery reached 20% state of charge.

$$s=(t+(0.65375(2.8c)) \tag{5}$$

Experiment Design

A comparison was made between a control run with no modulation and an experiment run using a single hormone to modulate speed as discussed in the previous section. The course was run over a series of repetitions of eight

Figure 17: A map of the course taken on Bala Lake to evaluate the performance of the hormone inspired power saving controller.

waypoints laid out in a transect style course, similar to those that would be used in a surveying mission. The course consisted of four 180 metre long parallel lines running northwest/southeast and 40 metres apart. A map of this course is shown in Figure 17. It was run on Bala Lake in north Wales on October 10, 2013, in calm water with wave heights under 10 cm and a wind of approximately Beaufort Force 3 from the north.

For this experiment, the software was told to consider the battery size to be 900 KJ instead of the actual capacity of 11,664 KJ. The onboard current and voltage sensors were used to calculate how much energy had been taken from the battery and to calculate the state of charge. The experiment was considered to be terminated when the state of charge reached zero. This reduction in battery size was undertaken simply to reduce the experiment run times and to ensure that the real battery was not completely discharged, something which could potentially damage the batteries. It can therefore be assumed that any timescales shown in these results could be multiplied by 12.96 to obtain a realistic figure for how they would behave with a full size battery.

Results

The results of the speed controlling hormone are shown in Table 5 and Figure 18. From Table 5, we can see that by introducing the hormonal control of the target speed we have extended the range of one battery charge from 3.9 to 5.4 km and increased the mission duration from 47 to 88 minutes. In Figure 18, we can see the rate of the battery discharge and how the speed changed during the experiment run. These results clearly demonstrate that this method allows for a gradual and almost continuous varying of power consumption and offers a much more subtle modulation method than having distinct low power and high power modes.

CONCLUSIONS

This work has demonstrated that the design of Minty2 is able to meet all the operational requirements set out in the “Hull Requirements” section. It provides a viable platform for operating in the dangerous environments in front of a calving glacier, achieving the target speed of approximately 4 knots, with more than ample capacity for carrying the survey equipment and sufficiently long endurance to carry out a typical survey mission and recharge without being taken out of the water. Although operations in Greenland were more limited than had been expected, she demonstrated that the design was suitable for an Arctic environment. Subsequent use in a variety of other locations

Experiment Title	Duration (Minutes)	Distance Covered (KM)	Joules per KM	Joules per Minute
Control	47	3.9	230769	19148
Experiment	88	5.4	166666	10227

Table 5: A table comparing the duration, distance covered, joules per km, and joules per minute of both the hormone controller and the control run.

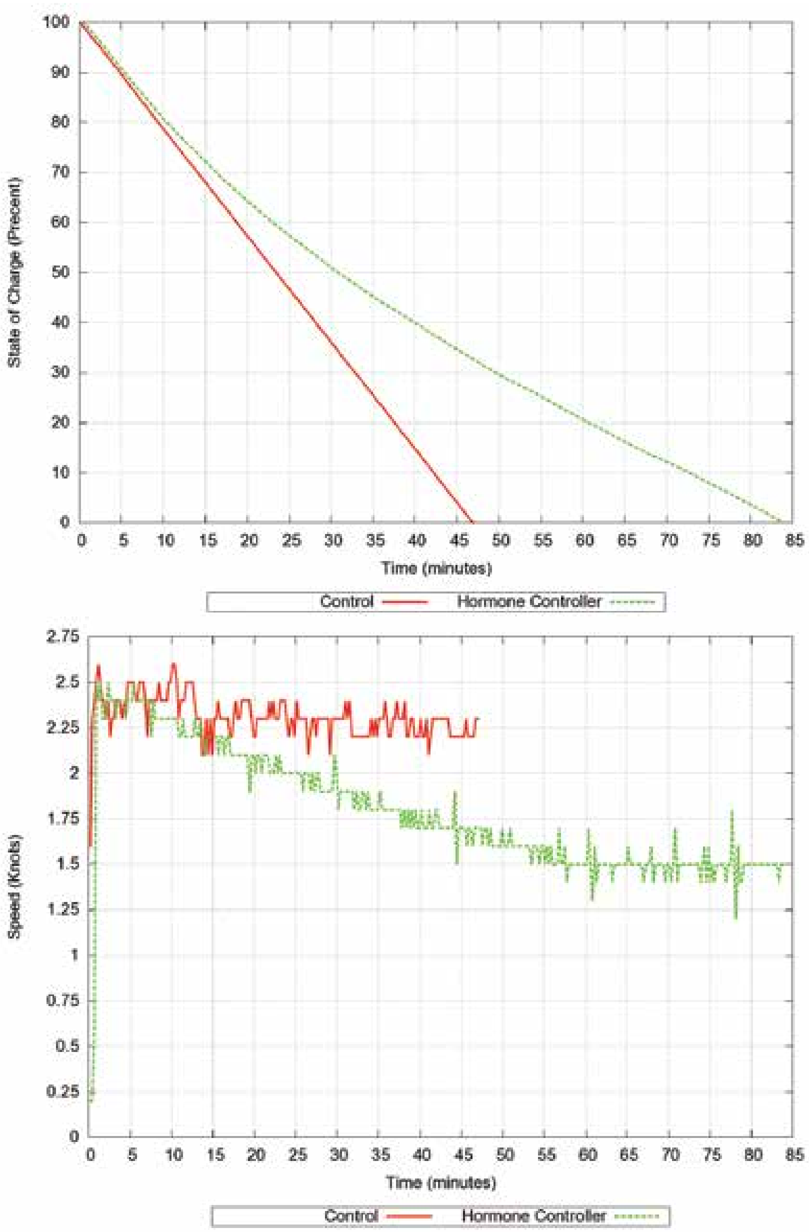

Figure 18: Graphs showing the speed of the boat and the battery discharge during control and experiment of the hormone controller experiment.

has shown Minty 2 to be a stable surveying platform, a durable design, easy to launch, tow and lift. She is versatile enough to perform survey missions in shallow waters and inaccessible locations, even when fairly long distance transits are required to reach the survey area. An autonomous control system has been developed that is capable of accurately sailing a course and offering manual tele-operation when required.

The development of a power management controller inspired by the mammalian endocrine system has demonstrated that power consumption can be managed in an analogue fashion, through gradual reductions in speed as batteries discharge and that this will boost overall range. Previous work on these techniques had used simulated (and somewhat unrealistic) battery data [Sauzé and Neal, 2011B; 2013; Sauzé, 2010] and to the best of the authors' knowledge, this work represents the first real world deployment of an artificial endocrine controller for power management based upon actual power consumption data and battery levels, further validating this as a practical technique for power management in autonomous robots.

To the best of the authors' knowledge, Minty2 represents the world's first autonomous surface vessel designed for operating in ice. Having already demonstrated that a small tele-operated vessel is a viable platform for surveying calving marine terminated glaciers, this work has shown that this role can be filled by an autonomous vessel which is much more capable of driving a straight course and being remotely monitored to avoid collisions with ice. The combination of both sonar and a laser scanner allows for a combined above and underwater survey to take place and high accuracy time synchronization and time stamping of IMU data insures that these can be correctly registered together.

The authors believe this work demonstrates that autonomous surface vessels are a practical method for safely surveying calving marine terminating glaciers.

Future Work

Avoiding large pieces of ice in the water must still be done manually at present and this requires constant supervision from an operator and tele-operation to perform an avoidance. If ice (and other obstacles) could be detected autonomously and short distance paths for avoiding them could be calculated, then it would be possible to avoid these autonomously, potentially allowing operations in less accessible locations where an operator might not have a direct radio link at all times and especially not one capable of showing high bandwidth video. This could be achieved through stereo vision [Larson et al., 2006], ultrasonic [Miller et al., 2010], or radar detection [Almedia et al., 2009] of obstacles.

Some changes to the boat's size and shape would help to improve the range of conditions in which surveys could be conducted and allow missions in less accessible locations. In particular, a lower freeboard would not catch the wind as easily, making the hull much easier to control in windy conditions. A better designed propeller could improve the efficiency of the propulsion. A smaller and lighter boat would also be better suited to survey missions in remote areas, especially in smaller lakes where a single hour of operation might be enough and in missions where there is no need for a laser scanner.

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